The Science of Material Failure Simulation

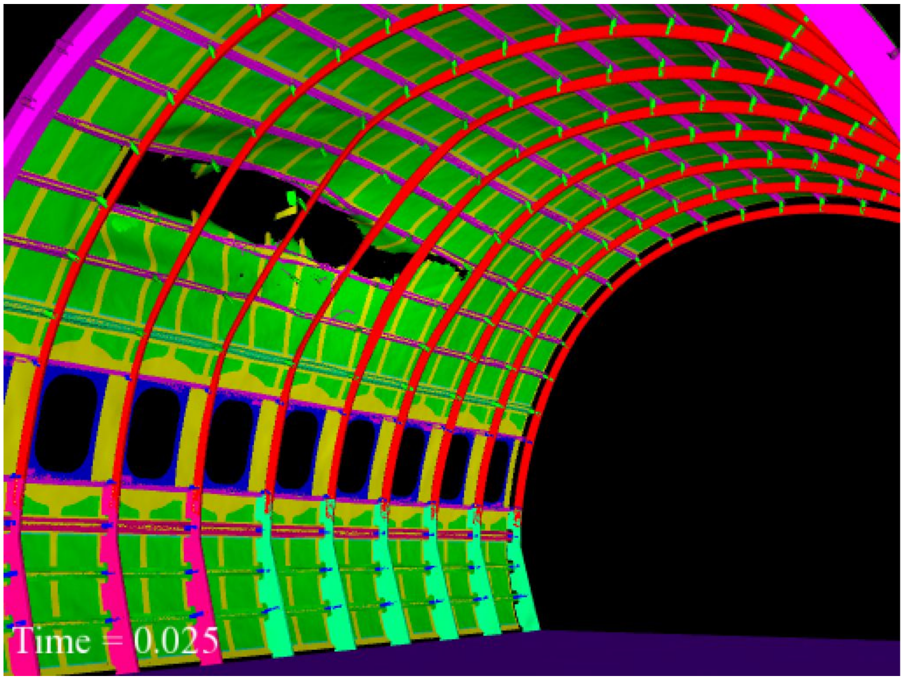

Figure 1: Simulation results showing tearing in an aircraft fuselage subjected to blast loading. Failure is represented using the element death technique.

Predicted behavior of materials under extreme stress is crucial to providing safety and security in weapons systems

For more information:

Technical Contact:
Ben Spencer
505-844-3778
bwspenc@sandia.gov
John Dolbow
505-845-0875
jedolbo@sandia.gov

Science Matters Contact:
Alan Burns
505-844-9642
aburns@sandia.gov

When structural systems are subjected to excessive or extreme loads such as blasts and high-velocity impacts, the process of material failure gives rise to an eventual loss in structural integrity. Computational science provides one of the most efficient means to examine what types of loads structures can sustain, as well as predict the effects of pervasive failure, should that occur.

Material failure is widely recognized as a multi-scale problem, linking the breaking of atomic bonds at the nanoscale to the growth of microscale flaws, to the formation and rapid propagation of cracks and free surfaces at the macroscale. Continuum-based models typically focus on material behavior at the microscale and above, employing phenomenological, constitutive models of the bulk response and failure criteria. The challenge for material failure simulation can thus be posed as: given a structural system consisting of known materials and a set of applied loads, predict the mechanical response including the transition to a highly disconnected state. Simulating the response of an aircraft fuselage to blast loading (Figure 1) is an example of such a challenge.

Numerical methods for this class of problems are typically based on discretizations of nonlinear partial differential equations. Well-known methods for continuum-based simulations of material failure include the finite element method and mesh-free/particle methods, as well as hybrid schemes. Under this broad umbrella, several specialized methods are distinguished by the means by which they describe the evolution of the system geometry as failure surfaces are introduced and evolved. A variety of these methods have been developed in the Presto code, which is part of Sandia's SIERRA Mechanics code suite. This code suite facilitates large-scale simulations and interaction with coupled field phenomena.

Sandia National Laboratories

LDRD
LABORATORY DIRECTED RESEARCH & DEVELOPMENT

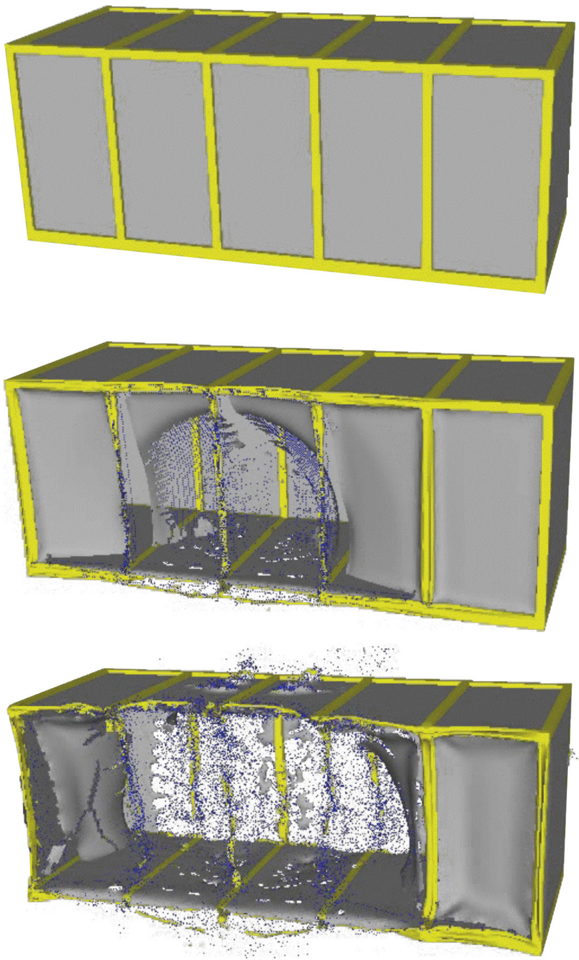

Figure 2: Simulation results of a thin-walled box structure with stiffeners subjected to blast loading showing progression of failure. Failed elements are converted to particles, and contact algorithms are used to prevent penetration of particles into solid material.

With finite element methods, perhaps the simplest technique to represent failure surfaces is known as "element death," wherein elements that are identified as "failed" are simply removed from the simulation. Particle methods often address material failure similarly, by removing communication links between nearby particles in the neighborhood of a failed region of material. For problems in which the contact of debris with intact material is important, failed elements can be converted to particles, as demonstrated in the simulation shown in Figure 2.

Element death techniques suffer from systemic problems such as mesh sensitivity and difficulties identifying unique failure surfaces from the collection of intact elements or particles. To overcome these problems, efforts using SIERRA Mechanics are currently focused on advancing the nodal-based extended finite element method (NBX-FEM). The method explicitly tracks failure surfaces, and enhances element-level kinematics to capture material separation (Figure 3). The bulk material response is carried at the nodes of the finite element mesh, facilitating topology updates when mesh distortion becomes severe.

The techniques discussed in this article will continue to be developed along with multi-length scale techniques that will allow for treatment of material heterogeneity, fine scale processes, and time scale issues. A major technical challenge that is being addressed is the elimination of "mesh" or model size dependence in the failure modeling process. With advancements in these areas, we will be able to predict failure for not only isolated single cracks, but also for problems of pervasive failure such as those associated with fragmentation and the subsequent damage that the fragments will create. This capability will be applied to a wide range of problems in the areas of nuclear weapon safety and security, and also a wide suite of national security problems associated with the Department of Defense.

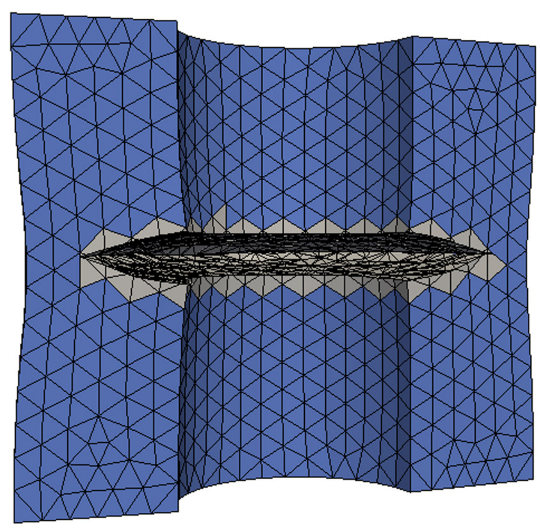

Figure 3: Deformed geometry for a thick-walled cylinder with a thumbnail-shaped edge crack. The gray elements are enriched with NBX-FEM kinematics.

Sandia National Laboratories

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. SAND2009-5577P

National Nuclear Security Administration

09/2009